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THE ORBITING SOLAR OBSERVATORY SPACECRAFT

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The first Orbiting Solar Observatory (OSO-1) was launched March 7, 1962, at 16:06 G.M.T. from the United States Atlantic Missile Range. This spacecraft was designed to point approximately 75 pounds of instruments at the sun with an accuracy of about 1 minute of arc. It accommodates an additional 100 pounds of instruments which are carried in a spinning section of the satellite which sweeps across the sun every 2 seconds. The total weight of the spacecraft is 458.3 pounds. In orbit it is 92 inches in diameter and 37 inches high. The spacecraft has on board data recording capability that can store 90 minutes of data. These data are played back over the spacecraft's transmission system in 5 minutes upon ground command. The spacecraft is in an almost perfect 300-nautical-mile circular orbit inclined 32.8° to the equator. The spacecraft has worked perfectly since injection into orbit and at the time of this writing has completed over 1,000 orbits. The pointing system has pointed the instruments at the sun with an accuracy of approximately 2 minutes in azimuth angle and 2.5 minutes in elevation. The temperature inside the satellite has stabilized to 5°C. Excellent radio transmission has been received from the spacecraft.

Author

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This paper describes the Orbiting Solar Observatory (OSO-1) spacecraft, with special attention to the features that are interesting to space scientists and reports upon the performance of the spacecraft in orbit.

Since the development of the high-altitude sounding rocket it has been possible for scientists to observe the sun from outside the main portion of the earth's atmosphere. However, sounding rockets allow only a fleeting glimpse of the sun and it has not been possible to make extended observations from outside the atmosphere. With the advent of the earth orbiting satellite, it was quickly recognized that long-term unimpeded solar observation was possible. One of the early programs of the National Aeronautics and Space Administration (NASA) initiated the development of an Orbiting Solar Observatory to furnish an observing platform for solar studies. On March 7, 1962, at 16:06 G.M.T. the first OSO was launched from the United States Atlantic Missile Range by a Thor-Delta vehicle.

The OSO-1 spacecraft was designed to point approximately 75 pounds of instruments at the sun with an accuracy of about

1 minute of arc. It also accommodates an additional 100 pounds of instruments which are carried in a spinning section of the satellite and sweep across the sun every 2 seconds.

A photograph of the spacecraft is shown in Fig. 1. The total weight is 458.3 pounds. With the arms extended, as shown, it is 92 inches in diameter and 37 inches high. The spacecraft consists of two portions; the "wheel," the lower nine-sided cylinder with three arms attached, and the "sail," the fan-shaped structure which is mounted above the wheel and which carries the pointed instruments and the solar cell array. The sail is attached to the wheel by a shaft running through the wheel. The wheel is free to rotate with respect to the sail.

In order to provide attitude stability, the wheel is kept spinning at 30 revolutions per minute. This spin rate is measured by optical rate sensors and is controlled to within ±5% by reaction jets which use compressed N_2 gas. The N_2 gas supply carried by the spacecraft is calculated to last at least 6 months. The angular momentum of the spinning wheel produces great gyroscopic rigidity and the spin axis tends to remain fixed in inertial space. Of course, there are various disturbance torques which tend to precess the satellite, but the precession rate is less than a degree per day. An active control system keeps the wheel's spin axis perpendicular to the solar vector to within 3 degrees in pitch. The angle between the solar vector and the spin axis is measured by optical error detectors. Whenever

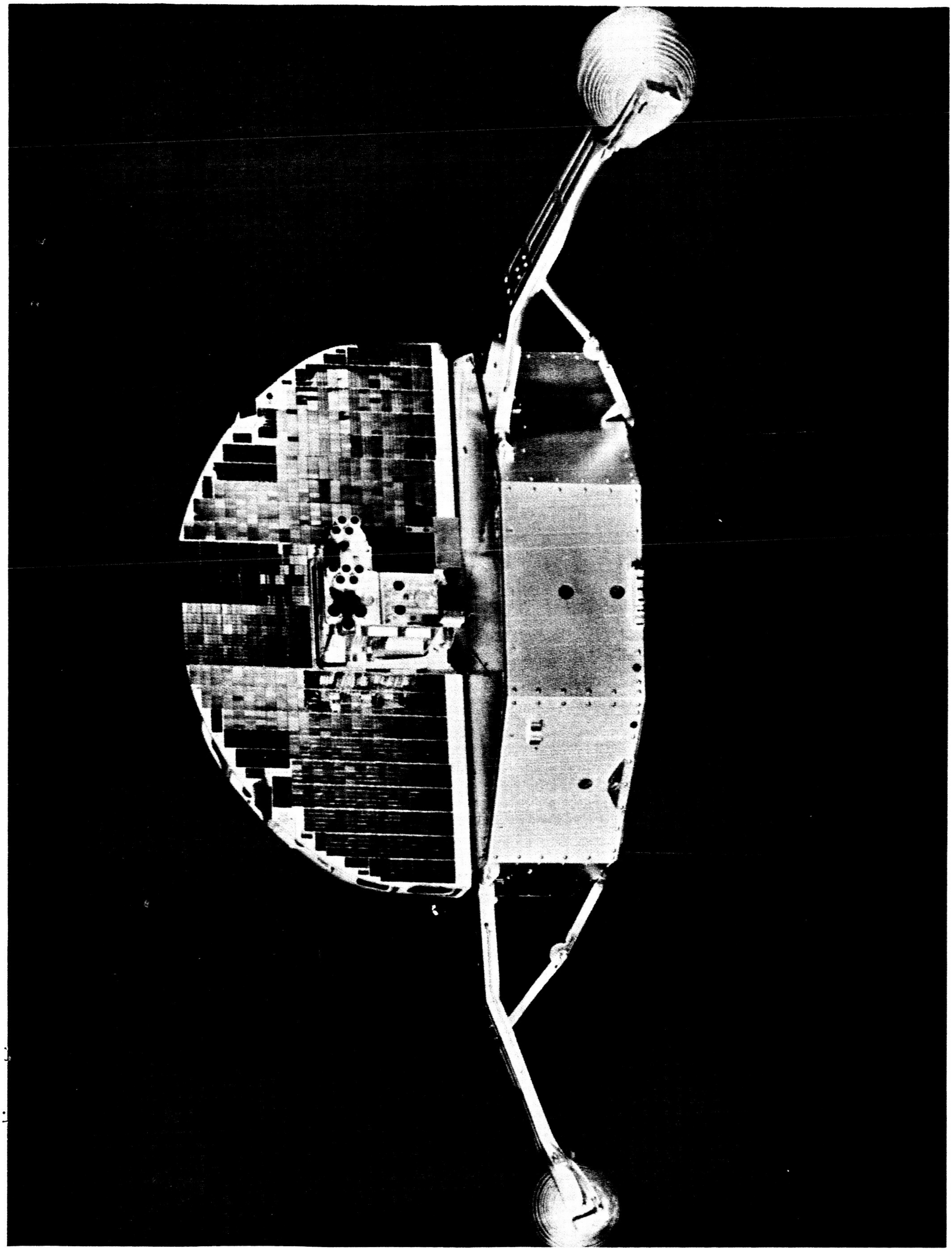

Fig. 1 - Orbiting Solar Observatory (OSO-1)

the angle exceeds 3 degrees, a second set of reaction jets is used to precess the satellite until the pitch error is corrected. The spacecraft is free to precess in roll about the solar vector but this rate is small. These axes are shown in Fig. 2.

The sail is free to rotate about the spin axis and is controlled by optical error sensors so that during the sunlit portion of the orbit, the plane of the sail is perpendicular to the solar vector. This is accomplished by a servo motor on the sail's shaft which drives against the wheel (the azimuth servo). The accuracy of this alignment is 1 to 2 minutes of arc. In the center of the sail is a gimbal which is free to move with respect to the sail in pitch. The pointed experiments are carried in this gimbal. A second servo motor on this gimbal shaft (the elevation servo) is optically controlled to align the instruments to the sun, again with an accuracy of 1 to 2 minutes of arc. The servo systems derive their error signals from two sets of photoelectric sensors. One set is mounted on the pointed instruments and the second on the sail. The set mounted on the instruments sense the angles between the direction the instruments are pointing and the sun, and produce a current output proportional to these angles. These detectors have a limited field of view but can measure angles of less than 1 minute. The set mounted on the sail is used to control the sail so that it is pointed at the sun within a few degrees. When

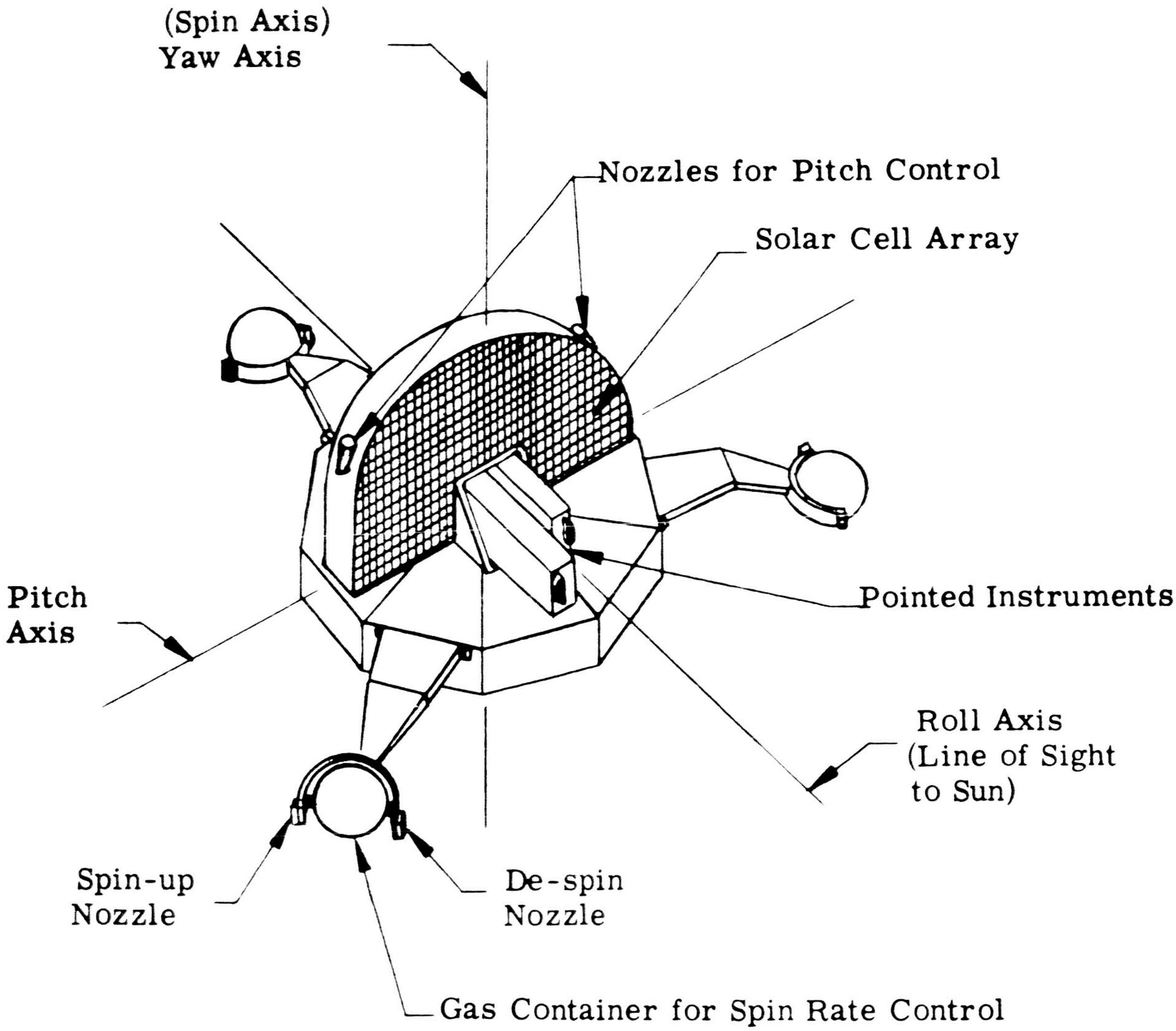

Fig. 2 - Axes, Orbiting Solar Observatory

this has been done, control is switched to the instrument detectors which will have the sun in their field of view. During the dark portion of each orbit, the servo systems are automatically turned off by a photoelectric switch. The sail is then allowed to spin with the wheel.

Each time the satellite passes from the dark to the sunlit portion of the orbit, the photoelectric switch turns on the servo systems. The azimuth servo stops the sail and aligns it so that the solar vector is normal to the plane of the sail. This is done under the control of the error detectors mounted on the sail. When the error detectors which are mounted on the instrument have the sun in their field of view, control is switched from the sail detectors to the instrument detectors. These detectors then control both the azimuth and elevation servos and align the instruments accurately to the sun. This acquisition cycle takes approximately 45 seconds.

The azimuth and elevation servo systems are designed to use a total power of less than 4 watts including the power used to drive the motors. This is accomplished by driving the azimuth and elevation motors by a pulse-width modulated power amplifier. The motors are driven by pulses which are always of maximum drive voltage but whose width varies depending upon the torque level required from the motor. This scheme eliminates power losses in the power transistors controlling the motors since they are either saturated or cut off.

Low power consumption also requires that all bearings, motor brushes, and slip rings have very low friction. This presents a problem since these components would ordinarily be sealed to protect them from the space environment. However, sealing these results in too high a friction level and hence in higher power requirements. To overcome this it was decided to operate all slip rings, motor brushes, and bearings exposed to the space environment. One of the most significant achievements during the OSO-1 development was the perfecting of treatments for these components which allows them to operate exposed to the low pressure of the space environment for extended periods of time and still maintain acceptably low friction levels. The treatments do not have any outgassing products which might contaminate the scientific experiments.

The pointed instrument gimbal can carry 75 pounds of experiments. These experiments are confined to a space 38" x 8" x 8". The OSO-1 spacecraft has 2 pointed instruments. One is an X-ray spectrometer which covers the spectral range 30 to 400 Å. This instrument weighs 20.5 pounds. The second instrument consists of several different experiments; solar X-ray (20-100 Kev and 1-8 Å) monitoring experiments, a gamma ray (0.510 Mev) monitoring experiment, an interplanetary dust particle experiment, and an experiment designed to monitor the aging of the photoelectric error sensors that are used in the spacecraft's servo system. This instrument weighs 45 pounds.

There are nine wedge-shaped compartments in the wheel. Of these nine compartments, five are available for scientific instruments. A total weight of about 100 pounds can be accommodated. The OSO-1 carries six different experimental packages in its wheel. These experiments were furnished by the Goddard Space Flight Center and Ames Research Center of NASA, the University of Rochester, the University of California, and the University of Minnesota. The location of these experimental packages and a brief description of each is shown in Fig. 3. The total weight of the wheel experiments in OSO-1 is 113 pounds. The other four compartments in the wheel are for the spacecraft's control, telemetry, data storage and command systems.

Since the wheel is spinning at 30 rpm and its spin axis is normal to the solar vector, each experiment in the wheel sweeps through the sun every 2 seconds. Also, the spacecraft is slowly rolling about the solar vector because of external torques and hence over a period of time, each wheel experiment will be able to scan the entire celestial sphere. This is extremely useful for experiments that wish to survey the sky or to compare the radiations and emissions from the sun to those from other regions of space.

OSO-1's solar cell array delivers approximately 30 watts of power at 20 volts to the spacecraft during the time it is oriented to the sun. The power is used to operate the control system, telemetry and experiments during the day and to charge

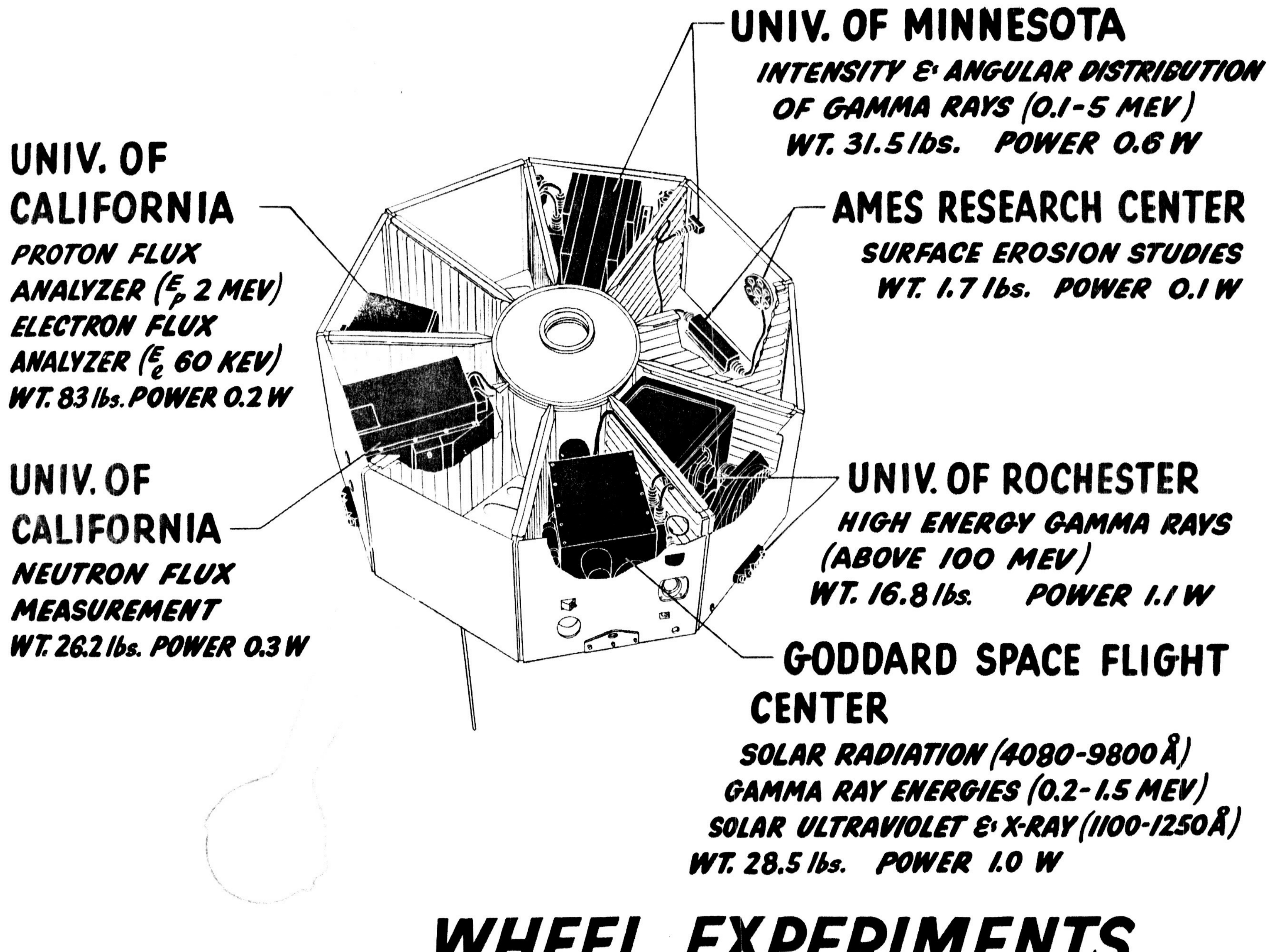
UNIV. OF MINNESOTA
INTENSITY & ANGULAR DISTRIBUTION OF GAMMA RAYS (0.1-5 MEV)
WT. 31.5 lbs. POWER 0.6 W
AMES RESEARCH CENTER
SURFACE EROSION STUDIES
WT. 1.7 lbs. POWER 0.1 W
UNIV. OF ROCHESTER
HIGH ENERGY GAMMA RAYS (ABOVE 100 MEV)
WT. 16.8 lbs. POWER 1.1 W
GODDARD SPACE FLIGHT CENTER
SOLAR RADIATION (4080-9800 Å)
GAMMA RAY ENERGIES (0.2-1.5 MEV)
SOLAR ULTRAVIOLET & X-RAY (1100-1250 Å)
WT. 28.5 lbs. POWER 1.0 W
UNIV. OF CALIFORNIA
PROTON FLUX ANALYZER (E_p 2 MEV)
ELECTRON FLUX ANALYZER (E_e 60 KEV)
WT. 83 lbs. POWER 0.2 W
UNIV. OF CALIFORNIA
NEUTRON FLUX MEASUREMENT
WT. 26.2 lbs. POWER 0.3 W
WHEEL EXPERIMENTS

Fig. 3

the nickel-cadmium batteries. During the dark period, the telemetry and wheel experiments operate from the storage batteries. Of the 30 watts, approximately 15 are used by the control and telemetry systems and 13 are used by the experiments. This allows 2 watts as a safety margin.

The telemetry system is FM-FM and has 8 channels; 6 channels are assigned to the scientific experiments, 1 channel is used for monitoring the spacecraft's operation, and 1 channel is used for a reference oscillator. Each experimenter is assigned a channel. The output of each experiment is conditioned to 0 to 5 volts and is used to deviate a subcarrier oscillator. The outputs of the 8 subcarrier oscillators are combined and recorded on magnetic tape by a tape recorder carried in the spacecraft. The reference oscillator referred to above is used for wow and flutter compensation of the tape recorder. The tape recorder can record for 90 minutes. Upon command from the ground, the tape can be played back in 5 minutes. When the tape is played back the output of the recorder is used to modulate a high power (1.75 watts) FM transmitter. In the record mode, data is being stored on tape and the signals are also used to modulate a low-power (250 milliwatt) transmitter so that real time information is available. Each part of the telemetry system; subcarrier oscillators, tape recorders and transmitters, is duplexed in the spacecraft. These spares can be substituted by ground command if the unit in operation fails.

Because of the increased speed of playback, the information rate into the tape recorder is limited. There is a total of 17.5 cycles (square wave) per second information bandwidths available to the experimenters. On OSO-1 this was divided as follows:

Goddard X-ray Spectrometer	6 cycles/second
Goddard Gamma Ray Experiment	4 cycles/second
University of California Proton, Electron, and Neutron Experiment	3 cycles/second
University of Rochester Gamma Ray Experiment	2 cycles/second
Goddard Gamma Ran, X-ray and Interplanetary Dust Experiment	1.5 cycles/second
University of Minnesota Gamma Ray Experiment	1 cycle/second
Spacecraft Monitoring Channel	1 cycle/second

Even with these seemingly small data rates, a large amount of data is collected by the experiments on OSO-1.

The OSO-1 is equipped with a tone-type command system capable of accepting 10 commands. These are used to initiate playback from the tape recorder, to interchange parts of the telemetry system and to turn on or off either all the wheel experiments or all the pointed experiments. These last 2 commands are incorporated so that if too much power is being used or if the power supply is not developing the proper amount of power, the experiments can be turned off to allow the batteries to be charged and then turned on again.

The spacecraft's temperature is controlled passively by controlling the ratio of the solar absorptivity of the surface to its emissivity. This is done by either covering the various surfaces with paint having the proper absorptivity-to-emissivity ratio or highly polishing the surfaces. In order to choose the correct ratio, a detailed mathematical analysis was made and the effects of changing the surface characteristics of the spacecraft were simulated using a digital computer.

The actual performance of OSO-1 has been most gratifying. The spacecraft is in an almost perfect 300-nautical-mile circular orbit, inclined 32.85 degrees to the equator. The perigee is 298 nautical miles and apogee 321 nautical miles. The period is 96.15 minutes. At time of injection, the spacecraft acquired the sun and all control systems and experiments worked perfectly. At the time this manuscript was written, the spacecraft had completed over 1,000 orbits and a preliminary analysis of the spacecraft's operation has shown all spacecraft systems and all experiments to be functioning properly.

The pointing accuracy in azimuth (about the spin axis) has ranged from 0.5 to 1.8 minutes of arc. The power required to drive the azimuth motor is approximately 3 watts, which is slightly more than expected. Fig. 4 shows the observed azimuth error angle and the azimuth drive power.

The elevation error has ranged as high as 2.5 minutes of arc and the elevation drive power has been as high as 4 watts. This is also slightly higher than anticipated and is attributed

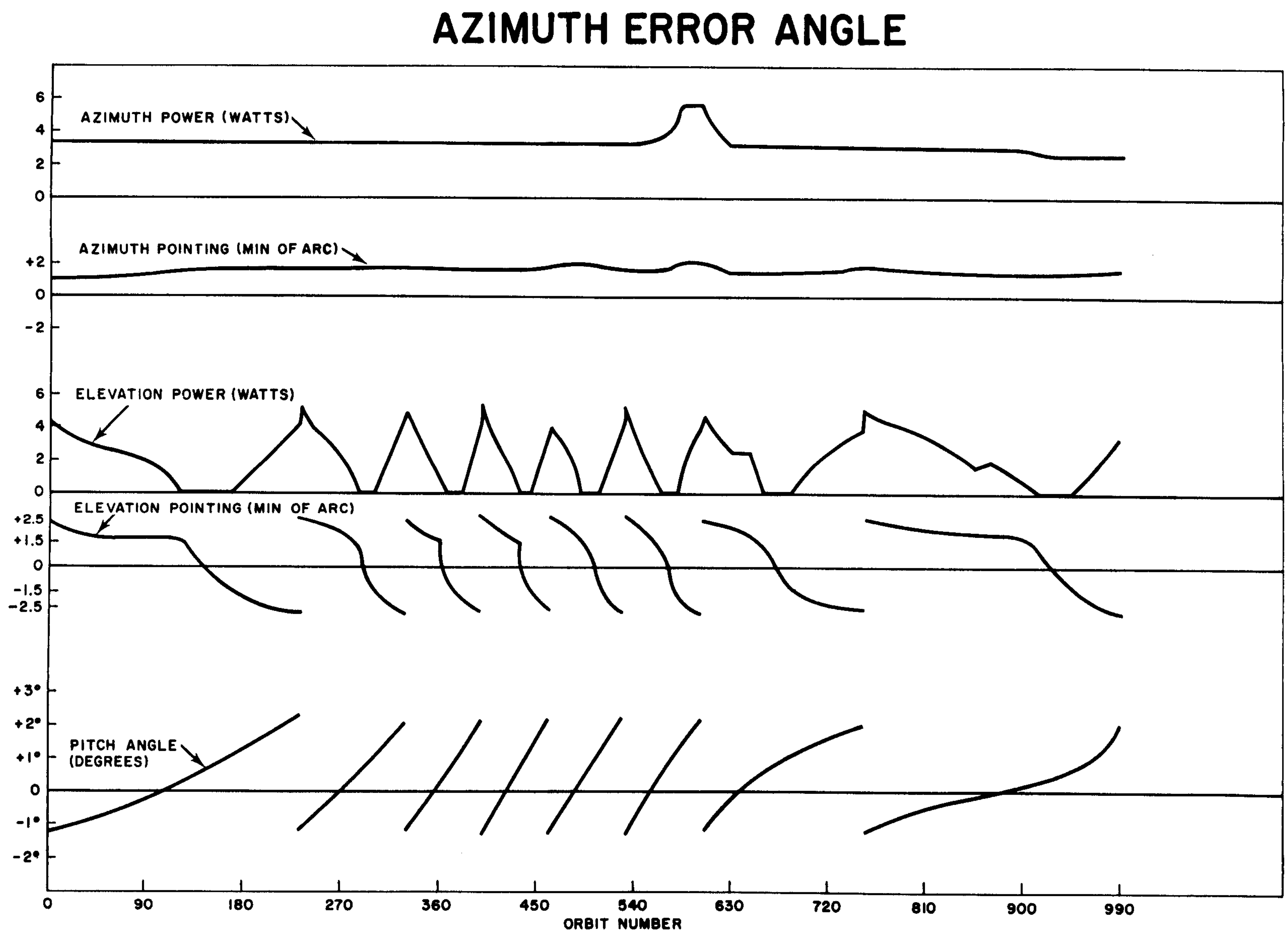
AZIMUTH ERROR ANGLE
AZIMUTH POWER (WATTS)
AZIMUTH POINTING (MIN OF ARC)
ELEVATION POWER (WATTS)
ELEVATION POINTING (MIN OF ARC)
PITCH ANGLE (DEGREES)
6
4
2
0
+2
0
-2
6
4
2
0
+2.5
+1.5
0
-1.5
-2.5
+3°
+2°
+1°
0
-1°
-2°
0
90
180
270
360
450
540
630
720
810
900
990
ORBIT NUMBER

Fig. 4

to excessive torque on the instruments from two flexible electric cables which lead from the instruments to the spacecraft's sail. These cables are colder than anticipated and it is believed that because of the cold they have become stiffer. Fig. 4 shows the variation of the elevation error angle and drive power with time. Also shown is the pitch angle of the spacecraft.

The rate of consumption of N_2 gas used to control the pitch angle and the spin rate is quite low. The spacecraft was injected into orbit with a pitch angle of about 3.5 degrees. The pitch control system corrected this to -1.0 degree, as it was designed to do, immediately after injection. No additional pitch gas was used until orbit 233, when again the pitch angle had increased to the allowable limit of 3 degrees. This amounted to a precession of about 0.25 degree per day. A third pitch correction was made during orbit 329. Between orbit 233 and 329 the precession rate averaged 0.67 degree per day. It is expected that the rate of change of the pitch angle will vary with time since it is a function of the angle between the spin axis and the plane of the ecliptic. When the spin axis of the spacecraft is normal to the ecliptic plane, there is no change in pitch attitude as the earth goes around the sun. When the spin axis is contained in the ecliptic plane, the pitch, if not corrected, will change about 1 degree per day because of the earth's motion around the sun. With the experienced gas consumption, the gas supply should last for longer than six months.

The solar power supply appears to be working very well. The nickel-cadmium batteries are being properly charged and their voltage ranges between 20.4 volts at the end of the day to 18.5 volts at the end of the night. This voltage swing is as expected and indicates that the batteries are not being severely discharged during the night. The solar cell array is running slightly cooler than expected which increases the solar cell output between 1 and 2 watts. The batteries therefore are being kept well charged. The temperature inside of the wheel is 5°C, which compares very well with the design temperature. The inside wheel temperature is essentially constant throughout the orbit. The temperature excursions of the outer panels of the spacecraft's wheel do not exceed 12°C throughout the orbit. Thirty orbits were required to reach equilibrium. The highest temperature reached on the solar cell array during the day is 60°C and at night the sail cools down to -38°C. The solar cell panel's rate of change of temperature as the spacecraft comes into the sunlight is about 7 degrees per minute. A temperature monitor inside the Goddard X-ray spectrometer indicates a temperature of about 7°C with only about ±1 degree change over the orbit.

The FM-FM telemetry system of the spacecraft has been most satisfactory. The signals received from the spacecraft at the receiving station during tape recorder playback have been strong and clean. A record of a data transmission received at the Fort Myers, Florida, receiving station compares favorably with one made in the laboratory during spacecraft checkout. It is possible to receive real time data transmissions from the spacecraft in Boulder, Colorado. The signal is sufficiently good that information concerning the operation of the spacecraft and the experiments is routinely being gathered at Boulder.

The OSO-1 command system is functioning properly but has been found quite susceptible to spurious commands. This was not unexpected since the same type of trouble occurred with the S-15 satellite which has the same command system. Because of this possibility, the commands were structured so that nothing catastrophic could occur to the spacecraft if the command system did accept spurious commands. This difficulty has been an annoyance but has not compromised the spacecraft's operation.

In summary, the OSO-1 was designed to provide a stabilized observing platform above the earth's atmosphere from which scientific observations of the sun and space could be performed. It is the first of a series of Orbiting Observatories which will progressively become more sophisticated, versatile, and useful. Operating experience with the OSO-1 has already given an observing time equivalent to that which could be obtained by nearly 4,500 Aerobee-Hi sounding rocket flights. This time has been furnished at a fraction of the cost of such a rocket program. The first Orbiting Solar Observatory has successfully performed its mission and has ushered in a new era in astronomy and astrophysics.

The authors wish to acknowledge the superb efforts of a great number of people from many different organizations who all worked together to bring about the successful launching of OSO-1.